This paper develops the fundamental technical limitations on band-sharing. It develops simple bandwidth and flux density scaling algorithms so that diverse system proposals can be compared on a level field with respect to these limited, allocatable resources. It provides the means to estimate the effect of a given band-sharing/flux density allocation on individual system and overall US capacity. While directed to the MSS issue, it develops a methodology that may be of use to the FCC in deciding how best to allocate and manage such common function, multiple entry band-sharing allocations in other bands as well.

The reader not interested in the detailed developments to follow in the next few sections may skip from this point to the final "RESULTS" section on page 10 for a summary of findings including specific examples.

CODE CORRELATION

Band-sharing SSCDMA users potentially interfere with one another in two ways. The first and easier part of the coordination problem is Code Correlation. In order effectively to separate the various band-sharing signals, the spreading codes must be essentially "uncorrelated". If two users were to utilize identical band spreading pseudo-noise waveforms or codes, they could (when inadvertently synchronized) interfere with one another totally, as if they were FDMA users in the same frequency channel.

Ideally, all user codes would be *orthogonal*, that is, correlation would always be zero. But this is not generally possible, both because of the limited number of such orthogonal codes, and because orthogonal codes are only so at a particular relative phasing with respect to one another. In the MSAT service, the relative phases of signals from different sources are position dependent. So a set of codes that were orthogonal in one location would not generally be so in another except in the special case of multiple downlinks from a single satellite. Practically, to realize the full advantages of SSCDMA band-sharing, users must utilize codes that do not correlate more strongly than random noise of the same power and bandwidth. This decorrelation can be effected by the use of "sufficiently" (can be rigorously defined) different code generators, frequencies, or phases. Considering these dimensions, there are potentially far more than enough pseudo-random spreading waveforms to go around, given some minimal structured coordination. Rules for such coordination need to be developed, however.

RANDOM CODE INTERFERENCE

The second aspect is more difficult and relates to control of cumulative background interference level. To a particular CDMA user, the signals of each other band-sharing user, CDMA or otherwise, appear as additional random, Gaussian noise. When the cumulative spectral density of all such band-sharing users exceeds the natural thermal noise background by more than a few dB, then the band is effectively saturated; practically, no more band-sharing is possible. To introduce more band sharers, or for any one user to attempt to increase his capacity by amplifying his signal level above this general background in an unregulated manner can only lead to an ultimately non-productive, mutual escalation of transmitter power without any gain in signal/noise ratio for anyone.

We will develop the fundamental governing relations for this band-sharing limitation hierarchically,

- starting with a single CDMA circuit,
- then a single CDMA cell,
- then a single CDMA system of regional cells,
- then a summation of regional CDMA (or other) systems, all sharing a common spreading bandwidth, W.

In this paper we consider only the satellite to user downlink because this commonly plays the critical role in capacity determination.

SINGLE CIRCUIT

First consider a satellite-to-ground circuit, with no intra- or inter- system interference from other users. The transmitted signal is idealized as uniformly spread over a bandwidth **W** with areal power spectral density at the mobile unit, ρ_1 ($w/m^2/Hz$). Then the available[2] signal power S_1 at the user antenna terminals can be expressed as

$$S_1 \quad = \rho_1 \, A \;\; W \qquad \text{(Watts)}$$

where

$$A \quad = \text{user receive antenna capture, area}$$
$$\doteq G_r \, \lambda^2 \,/\, 4\pi \qquad (m^2)$$

In the present instance we are dealing with systems (almost) all of which are designed to serve mobile, handset users. Consequently it is not unreasonable to assume that all the competing systems have about the same antenna gain (about zero dB +/-) and, of course, all are operating at the same wavelength, λ. Subject to possible exceptions requiring special treatment, we thus take the capture area, A, as a system independent constant for most mobile satellite systems in given band (AMSC may be a mild exception).

The available[1] system noise power spectral density at the same terminals may be expressed

[2]. The term "available" here means the maximum power available from the antenna to a matched load.

$$N_o = k\,T_o\,NF$$

where

$k\,T_o$ = reference temperature thermal noise spectral density (W/Hz)
NF = Effective system noise figure including external noise (other than CDMA interference)

All of the systems of interest are assumed digital at the baseband, so the relevant SNR-like parameter is the dimensionless bit energy-to-noise-density ratio, $\Gamma \doteq E_b/N_o$ given by

$$\Gamma = S_1 / (N_o\,R) \quad = \rho_1\,A\,W / (N_o\,R)$$

where R is the baseband digital rate.

To meet a suitable BER criterion, Γ is required to satisfy a certain minimum value, Γ_s, characteristic of the particular system (subscript s), typically 4 to 9 dB depending on details of modulation and coding. So we can solve for the required flux spectral density for a single circuit with no interference,

$$\rho_{1,s} \quad = \quad \Gamma_s\,N_o\,R / (A\,W).$$

Notation can be further simplified by defining an *effective thermal noise equivalent flux density,*

$$\rho_n \quad = \quad N_o / A$$

For a relevant example, consider N_o = kTo = -204.0 dBW/Hz, (i.e. thermal noise only), omnidirectional antenna at 2400 MHz. A = -29.0 dBm^{-2} and ρ_n = -138.9 dBW/m^2/4kHz. The high angle ITU flux limit, -144 dBW/m^2/4kHz, or 1 FDU, is thus 5 dB less than the thermal noise equivalent flux. Thus individual complying systems cause an interference level generally negligible as compared to thermal noise as clearly was the intention.

In these terms, the required flux density for a single signal (subscript 1) can be written:

$$\rho_{1,s} = \rho_n\,\Gamma_s\,\frac{R}{W} \tag{1}$$

In words, the minimum flux density for a single data channel is equal to the product of the equivalent noise flux density times the required Eb/No divided by the bandspread ratio, or processing gain, W/R.

SINGLE CDMA CELL

Now suppose that only one cell, that is one satellite beam, of one system is on the air. The system is subject to a flux density limit, ρ_s at the earth. How many circuits, M_s, can the system support in this one cell?

The thermal noise in this case is augmented by the CDMA noise from the other M_s - 1 circuits in system s. M_s is then given by the equivalent of Equation 1 above in which we substitute

ρ_s / M_s for $\rho_{1,s}$ (the single signal flux density)

and

$\rho_n + \rho_i$ for ρ_n

where

ρ_i = Interference flux spectral density
≡ $(M_s - 1) / M_s\ \rho_s$

Since M_s, the number of circuits for system s is generally much greater than 1 in the cases of interest, there is little error in assuming that the factor $(M_s - 1) / M_s$ is equal to 1. With these substitutions,

$$\Gamma_s = \frac{\rho_s \qquad W}{(\rho_n + \rho_i)\ M_s\ R}$$

or

$$M_s = \frac{\rho_s \qquad W}{(\rho_n + \rho_i)\ \Gamma_s\ R} \qquad (2)$$

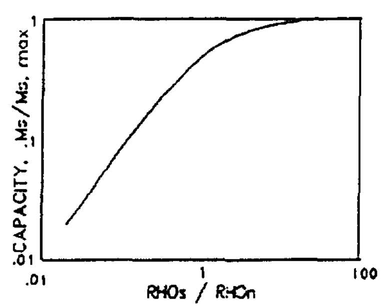
or

$$M_s = \frac{r}{1+r} M_{s_{max}}$$

where

$r \doteq \rho_s / \rho_n$ and $M_{s,max} \doteq W / (\Gamma_s R)$

This looks like this ---->>>>



For small ρ_s the capacity is proportional to ρ_s, that is, ultimately proportional to transmitter power. But as ρ_s becomes much larger than ρ_n, (the noise equivalent flux density) the maximum number of circuits supported by system s approaches the limiting constant,

$$M_s \rightarrow M_{max,s}$$

independent of ρ_s or transmitter power. Further increases in power, or flux density, ρ_s are unproductive in increasing system capacity since they raise the interference level as fast as the desired signal. Thus, $M_{max,s} = W / (\Gamma_s R)$, is the limiting CDMA circuit capacity of this simple, single cell example.

Some CDMA critics have noted that W/R is essentially the capacity of the same channel under Frequency Division Multiplex, and that therefore the limiting capacity of CDMA is smaller than FDMA by the factor $1 / \Gamma_s$. This would be true for a single cell system, but ignores the much larger gain in capacity due to frequency reuse factor that results from the unique CDMA ability to reuse the same spectrum in *each* cell of a multiple cell US coverage system.

SINGLE-SYSTEM, MULTIPLE-CELL REGIONAL COVERAGE

Generally, system regional capacity over an area such as the United States, can be increased by the use of small beams covering the region with a multiplicity of contiguous beams, that is, "cells". This provides a potential twofold advantage, 1) higher antenna gain, thus more total flux density for the same, limited transmitter power, (or lower power for the same flux density) and, 2) opportunity for reuse of the same spectrum in another part of the region. Both factors increase the total regional circuit capacity. Let NCR_s = Number of Cells per Region (e.g. United States) for system, s.

Frequency reuse among these cells, like co-channel reuse, comes at the cost of some additional co-channel interference. In general, and particularly in the case of FDMA where relatively little co-channel interference can be tolerated, it is necessary to put some distance, between co-channel users. The required distance separation in turn implies a "cluster size", NCC_s, (Number-of-Cells-per Cluster) which is defined as the minimum number of neighboring cells, each operating within a *different* subband, such that there be no co-channel interference between cluster members and that any cell outside the cluster is far enough away from a co-channel user within the cluster that his co-channel interference is tolerable. In the case of ground cellular users this cluster size is typically 7 or more. For FDMA satellite systems it may range from 3 to 7 while for CDMA systems it is generally but not always 1. We further define the Regional Frequency Reuse Factor, **RFRF** as

$$RFRF_s \triangleq NCR_s / NCC_s$$

A second important factor in consideration of regional coverage is "Cluster Overlap Factor", COF. It is possible in the case of CDMA to reuse the same frequency bands in every cell, that is, a cluster size of one. However, this is then at the price of possibly significant beam overlap or sideband spillover from one cell to the next. In the more general case of cluster sizes other than 1, the spillover from adjacent Clusters plays the same role. The effect of this spillover is a correspondingly increased background interference level and reduced circuit capacity. On the assumption of uniform loading of all cells, knowing the beam pattern, we can compute the amount of such spillover. We then define:

COF = Cluster Overlap Factor
$\triangleq$ (Total CDMA interference flux from all co-channel users in *all* clusters) / (CDMA interference flux from all co-channel users in *own* cluster)

In the common CDMA case where a cluster *is* a single cell, the word "cell" can be substituted for "cluster" in the above definition.

To the extent that COF is a function of position within a cluster (or cell), the system COF is defined at the worst spot in the cell, i.e. that for which COF is maximum.

If the system is subject to a maximum, allocated flux density limit, ρ_{m_s}, then the total interference flux is (at most) ρ_{m_s}, while the intra-cluster (i.e. from within same cluster) interference flux is ρ_{m_s}/COF. COF then is the amount by which the total flux per cluster (or cell) must be reduced due to finite beam spillover, in order to meet a prescribed maximum flux limit, ρ_{m_s} .

With these definitions, the per cell capacity is given by (2) above with the substitutions:

W/NCC_s	for	W	(Since only 1/NCC of the total bandwidth can be used per cell) and
ρ_{m_s}	for	ρ_i	(total interference limit)
ρ_{m_s}/BOF_s	for	ρ_s	(only the own cell useful part of the total flux)

and the total regional capacity, M_{r_s} is thus from Equ. 2:

$$M_{r_s} = \frac{\rho_{m_s}}{\rho_n + \rho_{m_s}} \quad Q_s \qquad (3)$$

where

$$Q_s \doteq \frac{NCR_s\ W}{\Gamma_s\ COF_s\ NCC_s\ R} \tag{4}$$

Q_s summarizes the intrinsic capacity determining elements of the system under the designers control, as opposed to the flux densities. It may be interpreted as the maximum possible regional system capacity if there were no flux density limits nor other band-sharing systems. Furthermore, within the above listed assumptions, it conveys all the necessary information about how effectively system s can share spectrum with other users. Notice that for the purpose of estimation, Q_s could be defined from equation 3 as the system capacity, normalized with respect to the system flux density as:

$$Q_s \doteq M_{r_s} \frac{\rho_{m_s}}{\rho_n + \rho_{m_s}} \tag{5}$$

This is used in the examples following.

For non-CDMA systems, essentially the same equation holds with the following understandings: 1) For FDMA and TDMA the overlap factor is essentially unity, because, in order to avoid unacceptable crosstalk, it is usually necessary that the co-channel interference be much smaller than random noise, 2) this is achieved by having a larger cluster size, NCC. In effect, overlap factor, COF, is traded for cluster size, NCC, and 3) system flux density, refers to the band average flux density, over the band, W. Thus the power areal density (integrating over the entire band, W) is , by definition, ρ W.

MULTIPLE SYSTEM, REGIONAL COVERAGE, FLUX ASSIGNMENT

Finally, we consider the case where multiple systems are assigned to the common band, W.

Inevitably, the flux density used by other users will reduce the capacity of each such band sharer system relative to what would be that case if that system had the band to itself. In the sharing mode, if there were no flux density allocations, or agreements, then, in principle it would be possible for one user to (temporarily) "steal" most of the inherent capacity of the band by increasing his transmitted power and flux density to well above that of the others. Ultimately, however, this could only result in a mutually fruitless escalation of power and flux density. No one would gain and all would lose power efficiency. Of course this would be to the detriment not only of the band sharers but of all other incidental interference victims, such as radio astronomy services etc.

This potential must be recognized and provided for by firm agreements or flux density allocations administered by the FCC. For the moment we assume that such individual system flux density limits are in place by one mechanism or another, each sharer system, s, being assigned and using a maximum flux density ρ_s. What is the resulting individual system and overall band capacity?

The total interfering flux density is given by the summation over all sharing systems of the individual system maximum flux density allocations

$$\rho_i = \sum_s \rho_{m_s}$$

Each system then must satisfy its own SNR requirements by restricting its capacity or number of circuits to that given by equation 2 above, except that now ρ_i and $\rho_s = \rho_{m_s} / \mathrm{COF}_s$ are set by allocation rather than necessarily the power limits of his own system or overall flux density limits such as the ITU limits.

That is, the regional capacity of the s[th] system is given by:

$$M_{r_s} = \frac{\rho_{m_s}}{\rho_n + \sum_s^{NS} \rho_{m_s}} Q_s \qquad (6)$$

For FCC purposes, the result of this sharing is best expressed in its effect on overall combined regional circuit capacity over a service region of interest such as the United States. The total regional capacity, summing over all systems is:

$$M_r = \sum_{s=1}^{NS} M_{r_s} \qquad (7)$$

If all sharing systems are allocated *equal* flux density, ρ_m so that

$$\rho_i = \sum \rho_{m_s} = \mathrm{NS}\,\rho_{m_s}.$$

Then from 6) , the individual system capacity reduction due to sharing would be in the ratio,

$$\frac{M_{r_{s_{shared}}}}{M_{r_{s_{alone}}}} = \frac{\rho_n + \rho_m}{\rho_n + NS\,\rho_m} \geq \frac{1}{NS} \qquad (8)$$

Thus the individual capacity of system s with sharing lies somewhere between that of system s alone and 1/NS of that alone. *If all systems were equal in terms of their individual regional capacities at the same flux limit, non-shared, then the total capacity with sharing would exceed the sum of the individual unshared capacities.* This unstated qualification is implicit in the abbreviated Loral-Qualcomm claim to this effect (Loral-Qualcomm consolidated reply, March 27, 1992, Technical Appendix, p.8). However, more generally, if all systems are *not* equal in terms of regional capacity, (or Q_s), then, allocating the same flux density to each, thus reducing each system capacity by the roughly the same ratio, even though that ratio is greater than 1/NS, *may result in a significant net loss of overall regional, i.e., US capacity* as compared to allocating strategies designed to encourage the development of higher capacity systems.

RESULTS

1.SYSTEM NORMALIZATION

With a few commonly applicable assumptions, equations 4 or 5, 6 and 7 provide the basis for comparing diverse systems on a level playing field with respect to their utilization of the allocatable resources, flux density and frequency bandwidth. Additionally they allow the comparison in terms of overall US benefit of various alternative allocation strategies.

The required assumptions for mobile satellite systems are that:

1. The system capacity is essentially determined by the limitations of the satellite-to-mobile down-link.
2. The system capacity is determined by flux density limits and not by available satellite power.

Both points are implicitly recognized by a majority of the current mobile satellite applicants, in that they and CELSTAR have proposed and requested variance above the one FDU or -144 dBW/m^2/4kHz ITU flux density limit. Even when the above two assumptions are not perfect it appears that they are a reasonable first assumption leading to a useful first approximation for the effects of system flux density and bandwidth normalization and-sharing.

Table 1 shows the results of the capacity normalizing algorithms given in the preceding sections. To make the normalization examples as relevant as possible, the comparison is put in terms of the actual design parameters of the major Mobile Satellite proposers. This requires abstracting from the documentation, three parameters:

- Total satellite-to-mobile Bandwidth, MHz
- Flux Density, dBW/m^2/4kHz at the ground
- US circuit capacity

for the Satellite-to-Mobile downlink, in order to evaluate the fundamental system capacity parameter, Qs, by equation 5.

It is not easy, and it may be impossible in some cases to extract these parameters unambiguously from the applications. In some cases there are partially alternative systems, or parameter update inconsistencies in various parts of the documentation. The data in columns B, C, and E of Table 1 are our best effort at extracting the correct and relevant parameters. Since inevitably there will be errors in this process we apologize in advance, will gladly correct them as informed, and ask the reader to regard the results as examples of a methodology based upon hypothetical systems which are generally like the actual proposed systems.

Under the above assumptions, for a given flux density, circuit capacity is directly proportional to bandwidth. So column F of table 1 represents the first step in normalizing the stated US circuit capacity, by linear proportion, to a common bandwidth, here taken as 16.5 MHz.

Column G is the system characteristic capacity, normalized to a common (infinite) flux density, i.e., Q_s, as given by equation 5, and common bandwidth, 16.5 MHz. This is the *limiting* capacity for very large flux density, (and satellite transmitter power) so may be well over the nominal capacity, particularly for systems such as ARIES, designed for significantly less than 1 FDU flux density. As a result of this normalization systems such as IRRIDIUM, ODYSSY, AMSC and CELSTAR suffer the greatest reduction of flux density from their original requests, and correspondingly greatest reduction of their nominal capacity. The flux density normalization implicitly assumes the feasibility of trading circuit capacity for flux density, which may not be the case for non-CDMA systems such as AMSC.

Column H of Table 1 is then the normalized real capacity of the system, reduced to common bandwidth, and a common nominal flux density of one FDU[1]. In all cases this nominal capacity is just 24% of the reference capacity, Q_s. It is suggested that comparison in this normalized form provides a fairer picture of the relative spectral utilization efficiency of the various systems. For example, it is seen that much of IRRIDIUM's high circuit capacity is related to its relatively large assumed flux density, about 13 FDUs. Accordingly, its 1 FDU normalized capacity suffers significantly. The bottom row (row 15) of column H is the summed capacity of all the proposed systems, each allocated 16.5 MHz and 1 FDU separately, US circuits.

2. Band-sharing EXAMPLES

Table 2 carries out several example joint allocations using this capacity renormalization methodology to illustrate the results of various flux density allocation strategies. For these hypothetical comparisons, we include only the clearly compatible, frequency duplexed, CDMA systems of Table 1, that is, GLOBALSTAR B, ELLIPSO, ARIES, ODYSSY, and CELSTAR.

In scaling the system capacities to various allocated flux densities according to equation 3, it must be borne in mind that flux densities *greater* than the design values would call for increased power and concomitant system redesign which might or might not be feasible, a separate question that would have to be investigated for each proposed allocation. Again, in this respect, the results are hypothetical, a first estimate, to be carefully reviewed for the applicability of other constraints in each case.

The first two columns (B and C) in Table 2 are the reference capacity, Q_s, and the capacity at nominal flux density of 1 FDU (the ITU high angle limit) for each system as derived in Table 1. Notice that the total normalized capacity of the systems separately at 1 FDU each is 40,298 circuits, given on the bottom line of column C.

Thereafter in Table 2, columns occur in pairs, representing respectively the assumed joint flux density allocation (measured in FDUs), and the resulting individual system capacity by equation 6. Total flux density and capacity over all systems are given in the bottom row.

CASE 1 is the nominal example of each system allocated and using 1 FDU shared over a common 16.5 MHz bandwidth. Total US capacity has decreased from 40,300 separately to 20,700 jointly, a 50% loss which also applies to each system individually due to the increase of total interference background from 1 to 5 FDU. The individual reduction factor may in fact be greater than this for GLOBALSTAR B since, by the use of orthogonal spreading codes on her down link, her self interference is much reduced and she suffers proportionately more in a sharing environment.

CASE 2 illustrates each sharer using two (as compared to one in CASE 1) FDU. This shows the saturation effect as doubling the flux density affords only a 25% increase in US circuit capacity. The point of significantly diminishing returns is somewhere around 5 FDU which is about equal to the thermal noise background flux equivalent, 138.9 dBW/m^2/4kHz.

CASE 3 illustrates the results of giving each system what they have asked for in terms of flux density. This is a total of 9.6 FDU and yields a total capacity of 34,000 US circuits. Note that this is about half that of CELSTAR alone, but at 4 times CELSTAR's proposed flux density.

CASE 4 illustrates an initial attempt at optimizing the allotted flux density shares, with an eye to maximizing overall capacity and affording a stronger incentive toward more spectrally efficient designs. In this case, the total flux density of 10 FDU is allotted in proportion to the normalized, reference capacity of the system, Q_s. Two things are obviously wrong with this: 1) It is much too strong an incentive, CELSTAR gets the lion's share of the flux, much more in fact than could be utilized within the overall prime power constraint of the CELSTAR design, and 2) the penalty on the less efficient system is so strong as to reduce ARIES, for example, to a single circuit; obviously non-viable.

CASE 5 is an attempt to do just a little bit of what CASE 4 was trying to do. In this case, the total flux of 10 FDU is allocated in proportion to the 0.15 power of the individual Q_s. In this case several of the systems come out reasonably close to what they have originally proposed.

Within the limited range of possibilities explored here, CASE 3, giving each applicant what they ask for in terms of flux density, within the general constraints of band-sharing compatibility seem to afford a reasonable solution. However this is at a sacrifice of almost half the potential capacity if it were possible to grant each system exclusive frequency bands. Clearly an optimum solution calls for some joint use of frequency division in addition to band-sharing.

IN SUMMARY

The era of band-sharing is here. New regulations and approaches to allocation are called for to make this work. The spectrum allocation problem must be seen to have acquired a new dimension, flux density, in which allocation is as important as the allocation of frequency band if the full potential benefits of band-sharing are to be realized.

In some cases band-sharing may result in overall gain in US capacity. In other cases it may have the opposite effect, loss of overall US capacity as well as individual system capacity and economic viability.

This paper does not develop or advocate any particular flux density sharing allocation policy. It does, however, provide the essential means to study the effect of different individual and total flux density allocations on individual and total US capacity.

Some such methodology is seen as an essential element in realizing the FCC objective of managing the RF spectrum to the maximum overall national benefit.

TABLE 1

	A	B	C	D	E	F	G	H
1		INDIVIDUAL SYSTEMS NORMALIZED						
2							Qs	Ms
3		DESIGN PARAMETERS				BW	BW & FD	@ FD =
4						NORMALI	NORMALI	1 FDU =
5						Bo=	FDnoise=	-144
6		BW	FLUX DEN	FLUX DENS		16.5	-138.9	
7		MHz	dBW/m2/4	FDUs (1)	US CKTS	US CKTS	US CKTS	US CKTS
8	IRRIDIUM	10.5	-132.8	13.18	3835	6026	7506	1772
9	GLOBALSTAR	16.5	-145.0	0.79	5000	5000	25369	5989
10	ELLIPSO	16.5	-144.0	1.00	864	864	3660	864
11	ARIES	16.0	-148.6	0.35	50	52	533	126
12	ODYSSY	16.5	-137.4	4.57	4600	4600	7857	1855
13	CELSTAR	16.0	-139.4	2.88	60905	62808	133280	31464
14	AMSC	14.0	-139.0	3.16	3000	3536	7154	1689
15	TOTALS				71419		170699	40298

16 1. FDU: Flux Density Unit equal to -144 dBW/m^2/4kHz

TABLE 2

EXAMPLES OF JOINT ALLOCATION

	A	B	C	D	E	F	G	H	I	J	K
1				CASE 1		CASE 2		CASE 3		CASE 4	
2		Qs	Ms,144	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd
3	SYSTEM	US Ckts	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts
4	GLOBALSTAR	25369	5989	1	3080	2	3833	0.8	1522	0.74	1469
5	ELLIPSO	3660	864	1	444	2	553	1.0	277	0.11	31
6	ARIES	533	126	1	65	2	81	0.3	14	0.02	1
7	ODYSSY	7857	1855	1	954	2	1187	4.6	2713	0.23	141
8	CELSTAR	133280	31464	1	16183	2	20139	2.9	29041	3.90	40549
9	TOTAL	170699	40298	5	20726	10.0	25793	9.6	33567	5	42190
10											
11		CASE 5		CASE 6		CASE 7		CASE 8		CASE 9	
12		FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd	FDalloc	Ms, shrd
13	SYSTEM	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts	FDUs	US Ckts
14	GLOBALSTAR	1.2	3561		0		0		0		0
15	ELLIPSO	0.8	349		0		0		0		0
16	ARIES	0.5	35		0		0		0		0
17	ODYSSY	0.9	872		0		0		0		0
18	CELSTAR	1.6	26068		0		0		0		0
19	TOTAL	5	30885	0	0	0	0	0	0	0	0
20	* 1 FDU := -144 dBW/m ^ 2/4kHz										

APPENDIX D

CELSAT INTERFERENCE ANALYSIS & COMPATIBILITY WITH OTHER SYSTEMS

The compatibility of applicant's proposed system with other systems in both the preferred bands of operation, 2.4/2.1 GHz, and the alternative bands of operation, 1.6/2.4 GHz, is discussed in this appendix. Most of the discussion and analysis in the downlink direction is contained in Appendix C as the demonstrations of compatibility and the levels of interference are related to the requested relaxation of power flux density.

Proposed Uplink Band

Applicant's proposed uplink band of operation is in the 2410-2428 MHz band. This is in the upper half of the 40 MHz band from 2390-2430 MHz that the US delegation to WARC-92 will propose for generic MSS in the earth-to-space direction. Currently, this band is shared by government radiolocation systems and amateur services. The government allocation is primary and is limited to military systems by footnote G2. The amateur services include the amateur-satellite service. As these services have secondary status they are not considered further in this analysis.

Analysis of the compatibility and the potential for interference with military systems will be conducted by Celsat if the Commission makes the characteristics and locations of the systems available. We note that, in its report on the WARC-92 preparation inquiry, the Commission did not cite any DoD comments concerning the US proposal that the band be allocated for non-government mobile-satellite services. From this it is inferred that a problem in sharing the 2390-2430 MHz band with military systems operating in the 2390-2450 MHz band does not exist.

Alternate Uplink Band

As an alternative to the 2410-2428 MHz band, applicant requests that its operations be located in the RDSS band, 1610-1625.5 MHz. Compatibility and the potential for interference to and from systems in the various services now occupying this band are discussed infra.

The US proposes to upgrade the Radio Astronomy (RA) service in the 1610.6 to 1613.8 MHz band to primary status; this would be effected by modification of ITU footnote 734. 1/ No US footnote to the 2.106 table identifies RA operations at any of the radio astronomy observatories or other facilities for the 1.6-GHz band such as those mentioned for other bands in FNs US111, US203, US256, US257, and US311. However, the NAS/Geostar agreement offers guidance in this regard. 2/ Applicant's proposed division of the uplink band into subbands will assist in preventing harmful interference to spectral line observations by avoiding use of the lowest subbands in areas in which RA may be operating. Applicant's uplink operations do not actually use the lowest 1 MHz of the band and begin at 1611 MHz, dividing the spectrum above this into 1.25-MHz subbands. The proposed subband assignment is dynamic and flexible; the lowest three subbands will not be assigned during periods of RA operation in affected areas. In this manner no transmissions will occur below 1614.75 MHz. Time sharing of the RA band has been suggested. 3/ Celsat's transmission modes make time sharing of the RA band infeasible and no attempt to take this approach will be made. In this manner, Celsat's operations will not decrease RA observation time in the 1.6-GHz band. Celsat's proposed ground channels and access channels are located at the upper edge of the band and will not interfere with RA operations. Applicant can modify operations rapidly, on short notice, to accommodate temporary RA operations at any location, and will design the Celsat system to avoid harmful interference with any existing or future permanent RA operations within any of its service areas. Note that applicant will use the 1.6-GHz band only for ground user terminals and will not conduct space or airborne operations in this band that, as FN 734 observes, are "particularly serious sources of interference" for the RA service.

The US WARC-92 delegation is empowered to protect the Soviet Global Orbiting NAvigation Satellite System (GLONASS) if it operates above 1610 MHz. 4/ This would appear to be the case; ARINC states that GLONASS operates at ten center frequencies in the band from 1610.44 to 1615.5 MHz. 5/ It transmits spread-spectrum modulation in wideband (P) and narrowband (C/A) modes similar to the US' Global Positioning System (GPS) at a signal level of -44 dBW/Hz with RHC polarization. 6/ The P-code transmission mode has its first spectrum nulls at +/- 5.11 MHz, the C/A mode operates at one-tenth the P-mode rate and its spectrum is scaled accordingly. GLONASS will be used on US aircraft to supplement GPS for navigation. In addition, GLONASS and GPS may be used at US airports to monitor runway activity and thereby avoid collisions between departing or landing aircraft and ramp service vehicles. The potential for harmful interference from handhelds operating at 1.6 GHz is examined infra with respect to navigation aboard aircraft; interference with ground-based receivers for collision avoidance will be less severe because the excess path losses will be greater than that assumed in the analysis for an aircraft above the ground.

GLONASS satellites orbit at 19,200 km and transmit to earth using 13-dB isoflux antennas. ARINC Characteristic 743A 7/ requires the aircraft receiver to track a GLONASS signal received at the -139 dBm level subject to in-band interfering signals 13 dB above this level, or at -126 dBm.8/ The aircraft antenna gain is not specified below its local horizon, at which point the gain is specified to be at most -5 dBi; this value is used as a worst case since the path to a handheld will be below the local horizon except when the aircraft is banking in the direction of the handheld. Applicant's typical handheld will, when communicating with a satellite, transmit with a net EIRP of -9 dBW, or +21 dBm. The aircraft's navigation receiver will use the GLONASS C/A signal and will require approximately 0.5 MHz bandwidth. A handheld will have a subband spectrum about twice this and a 2:1 bandwidth advantage is given to the navigation receiver when estimating the potential for interference.

At a 1-mile horizontal separation from an airborne GLONASS receiver, the handheld signal is received at a level estimated as:

Pr = +21 - 116 (path loss) - 5 (gain) -3 (advantage) = -103 dBm.

The path loss is the per-mile free-space value at 1610 MHz plus 15 dB excess path loss for an assumed aircraft altitude of 30 meters (about to land or taking off). The excess interference level is the difference between the -103 dBm level and the acceptable level of -126 dBm. The 23 dB excess is eliminated at a separation of about 6 miles, assuming a 30-dB/decade propagation law. 9/ For aircraft at higher altitudes, the excess path loss will diminish, approaching 0 dB above an elevation angle that will be related to the nature of the surrounding terrain. But at higher elevation angles, the entry angle to the aircraft's GLONASS antenna falls below the horizon. For lack of more detail concerning the aircraft antenna's gain below the horizon, it is assumed that the two factors, excess path loss and sub-horizon antenna gain, offset one another and the 6-mile separation holds for all handheld/aircraft aspects. Thus, a handheld operating near an airport may cause harm to navigation if the aircraft cannot use the US' GPS system that operates outside the 1.6-GHz band. This is a matter for additional study but can be alleviated by operating handhelds in subbands above 1615.5 MHz when near GLONASS receivers. In any event, in light of the demise of the Soviet Union and the subsequent financial problems of the CIS, reliance upon GLONASS for US domestic operations, especially those relating to public safety, is misplaced and will probably diminish. The third-generation Inmarsat system to be launched in 1995 will have a GPS/GLONASS "overlay" capacity that will provide an alternative to GLONASS. Further, use of the US' GPS system could provide twice the location accuracy if the "selective availability" imposed by the DoD is suspended. 10/

GLONASS' interference to Celsat's satellite transponders may cause harm, based on the following examination. The worst case approach between a GLONASS satellite and that of Celsat occurs when a GLONASS satellite is on the opposite side of the earth from a Celsat satellite. For a Celsat beam serving Anchorage, the squint angle to the earth's limb is within the main lobe of a beam centered on Anchorage and is approximately 10 dB down from the maximum gain of 46.6 dBi. The beamwidth of the GLONASS antenna exceeds that required to subtend the earth from limb to limb and an orbital arc of many degrees will exist during which the excess beamwidth can illuminate the Celsat satellite and create substantial interference. At a typical separation of 66,000 km, the interference density is -191 dBW/Hz at the Celsat antenna terminals and is about +37 dB with respect to Boltzmann's constant, thereby raising the system noise temperature from a nominal 528 degrees K to over 5000 degrees K. The self noise from a fully loaded satellite cell ranges from -186 to -181 dBW/Hz, depending on the activity in adjacent cells. The interference can reduce the nominal 1.7-dB margin on the return link (handheld to node) by from 0.4 to 1.2 dB. The situation is worse if two or more of the planned 21 GLONASS satellites are in view of the geostationary satellite. Since the GLONASS carrier spacings are 0.5625 MHz and the C/A-mode spreading bandwidth is about 1 MHz, there is a likelihood of interference overlap into one of the Celsat 1.25-MHz subbands. This interference problem can be avoided by assigning only subbands above 1616 MHz in Celsat's northern-most beams.

GLONASS officials are reported to be aware of these problems; in subsequent system designs they will not use carriers above 1610 MHz and will take actions to protect the geostationary arc. Such remedies are not available in the short term, however.

International footnote 733 allocates the 1610-1626.5 MHz band to the aeronautical mobile-satellite (R) service on a primary basis, worldwide. The potential for interference from applicant's use of this band can be estimated as follows: Assume an AMS(R) satellite having an antenna that views all of CONUS and therefore having a gain of approximately 30 dB. Assume a 10-kbps data channel and a satellite reception bandwidth of 20 kHz using a receiver with a 3-dB noise figure. The noise floor is -158 dBW. Assume that the encoding and modulation are such that the required CNR is +6 dB for the specified data bit-error rate. If the AMS uplink is operating with no remaining margin the desired signal is received at a -152 dBW level. If all of applicant's 60,900 satellite channels are in use, the worst-case interference level will occur. In any of the ten subbands there will be 5,700 channels, each in view by the AMS satellite, and each with an nominal EIRP of -9 dBW. The total uplink interference power is -9 + 10 log 5700, or +28.6 dBW. The effective power inband at the AMS receiver is adjusted by the ratio of Celsat user spreading bandwidth to the reception bandwidth, or by -18 dB (ratio of 20 kHz to 1.25 MHz); the effective interference power is therefore +10.6 dBW. The path loss to the AMS satellite is 188 dB and the received power is +10.6 -188 +30, or -147.4 dBW. The C/(N+I) level for the assumed 0-margin operating point is -4.6 dB. However, there are several mitigating factors to consider. If there is a difference in polarization type between the AMS link and the Celsat link (which is RHC) at least 3 dB improvement can be realized. The AMS link may be operating above its 0-dB margin, and, further, all 57,000 Celsat channels are not likely to be active at the same time. Applicant will take care to coordinate with any and all AMS(R) systems that may be proposed or come into being in order to ensure the integrity of each such system.

Compatibility with other systems and the potential for harmful interference from applicant's system in the downlink direction in the 2110-2130 MHz band and in the 2483.5-2500 MHz band are discussed and analyzed in Appendix B.

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1. WARC-92 Preparation Inquiry in Gen Docket 89-554, June 20, 1991, at 42.

2. Six observatories were identified in the agreement, two in California, one each in New Mexico, Texas, West Virginia, and Puerto Rico. A 25-km protection radius must be observed during periods of observation in the 1610.8-1613.8 MHz band about geographical coordinates specified for each of these sites. The Celsat emission characteristics and user geographical density are different from those of Geostar and the protection radius may differ from the 25-km value arrived at in the Geostar agreement.

3. Avoiding transmissions during the first 200 milliseconds of each Coordinated Universal Time second allows the radio observatory to gather line-spectrum data and has been authorized as a method of coordination; see Appendix D of RDSS Report & Order, July 25, 1985, in Gen. Dockets 84-689 & 690.

4. WARC-92 Preparation at 41.

5. According to ARINC in its Reply Comments of July 3, 1991 to the Iridium and Ellipsat applications.

6. Dale & Daly, "The Soviet Union's GLONASS Navigation Satellites," IEEE AES Magazine, May, 1987, pp. 13-17.

7. Draft copy informally obtained; 743A is yet to be published and therefore the specifications cited supra are subject to change.

8. The GLONASS spreading sequence is 511 bits; we assume a processing gain for the GLONASS receiver equal to its despreading bandwidth reduction, or 27 dB. This would account for the ability of the receiver to operate while subject to interference at a -13-dB I/C level.

9. This is in agreement with the propagation model shown as Figure 2-8 in Lee (Mobile Communications Design Fundamentals, Sams & Co., 1986). An average between the open-area and suburban-area excess loss at 1 mile is about 10 dB for a mobile antenna at 3 meters height and a 30-meter base station antenna height. Adjusting for the proposed operating frequency and the lower height at which a pedestrian user would hold the handheld, an additional 5 dB should be ascribed to the excess loss.

10. GPS has twice the spreading bandwidth of GLONASS and similar parameters otherwise. Hence the temporal resolution is twice and should translate to approximately twice the location accuracy. Selective availability deliberately reduces the inherent accuracy to less than that obtainable from GLONASS.